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CFD-Based Power Analysis on Low Speed Vertical Axis Wind Turbines with Wind Boosters

Natapol Korprasertsak[a*], Thananchai Leephakpreeda[a]

[a]*School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, P.O. box 22, Thammasat Rangsit Post Office, Pathum Thani, 12121, Thailand*

Abstract

In many accessible regions of Thailand, the average wind speed is generally quite low. Although Vertical Axis Wind Turbines (VAWTs) are designed for performing mechanical work acceptably at higher wind speeds, they are usually chosen to be installed for those areas where the local wind speed is low as well. Therefore, standalone VAWTs are still unable to generate mechanical power satisfactorily for best practice. This study introduces analysis of effect of wind boosters on power generation from vertical axis wind turbines (VAWTs), by utilizing Computational Fluid Dynamics (CFD) software. A wind booster is invented for incorporating with a VAWT in order to not only overcome limitations of harvesting energy with low availability at low wind speed but also enhance performances of a VAWT at higher wind speed. Specifically, a wind booster has numbers of guide vanes installed around a VAWT. All the guide vanes direct wind to impact VAWT blades at effective angles while passages between each guide vane are designed to throttle wind so as to accelerate air flow before impacting VAWT blades. From CFD case studies, guiding and throttling effects of the wind booster are able to increase angular speed of a VAWT which leads to increase in mechanical power generated from a VAWT.

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Keywords: low wind speed; wind booster; vertical axis wind turbine; computational fluid dynamics

1. Introduction

In Thailand, the average wind speed is relatively low, approximately with 2-3 m/s at height of 20 m; therefore, Vertical Axis Wind Turbines (VAWTs) are chosen to be installed because those wind turbines

* Corresponding author.
E-mail address: lopatan.tam@gmail.com

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are designed to yield just acceptable performances on mechanical works at not high wind speeds. However, standalone VAWTs are not sufficient for the most effective wind power conversion, so it is necessary to invent a wind booster that can improve performances of VAWTs in order to overcome the limitation of harvesting energy with low availability at low wind speeds.

There are a few relevant researches in attempting to improve performances of VAWTs at low speed conditions. Takao, M., et al [1] developed an air flow controlling device called a "directed guide vane row". This straight-bladed mechanism is inherently constrained due to the design; it can capture a wind stream only in a single direction of a VAWT. Chong, W.T., et al [2] developed omnidirectional guide vanes, which can greatly increase power output of a VAWT. Also, Pope, K., et al [3] introduced numerical analysis to determine operating angles of stator vanes for a VAWT. Although those devices can capture wind in all directions, proper arrangements of guide vanes are not concerned for best practice in those studies. Additionally, Ohya, Y. and Karasudani, T. [4] developed a shrouded horizontal axis wind turbine system called "Wind-lens turbine". It can be learnt that wind can be speeded up by a shaped passage even though the design is not applicable to VAWTs.

In this study, a wind booster is developed in order to improve angular speed of the VAWT which leads to increase in mechanical power generated from the VAWT. By using specially-designed guide vanes, the wind booster can control flow direction and accelerate wind from any directions in order to yield effective impacts to VAWT blades.

2. Methodology

In this study, CFD simulation of a VAWT coupled with a specially-designed wind booster is performed in order to analyze what effects on air streams that lead to an increase in the overall angular speed of a VAWT at low wind speed conditions of 1 m/s to 8 m/s. Actually, there is another typical method, which is able to increase power output of VAWT by enlarging size of turbine. However, the reasons to increase wind speed are: 1.) The relationship between wind speed and wind power is "power is proportional to wind speed^3"; therefore, increasing wind speed can greatly multiply power output of a VAWT compared with an increase in size of a turbine. It can be expressed as:

$$P = 0.5\rho A v^3 \tag{1}$$

where P is the available wind power (W), ρ is the air density (kg/m^3), A is the frontal area of the VAWT (m^2), and v is the wind speed (m/s).

2.) This method does not require a large wind turbine, which means savings both cost for material and space for installation. Also, it may not be workable at low wind speed owing to hard start-up of large inertia.

2.1. Design of wind boosters

The concept for designing a wind booster is to not only guide wind to blades of a VAWT but also increase wind speed before engaging to a VAWT. As shown in Fig 1 (a), guide vanes with curve sided triangle shape are designed to direct air streams to turbine blades properly. To increase wind speed, the guide vanes are arranged to throttle air streams. Since wind can blow to all 360 degree direction of a VAWT, the blades of guide vanes are set up around a VAWT. The assembly under working conditions is illustrated in Fig 1 (b). The VAWT is mounted at the middle of the wind booster. It rotates about the vertical axis while the wind booster is fixed at the position. The upper and lower rings are used to fix all the guide vanes at certain positions around the wind turbine as illustrated in Fig 2.

Fig. 1. Function and structure of wind booster. (a) Wind blowing through wind booster; (b) Assembly of VAWT and wind booster

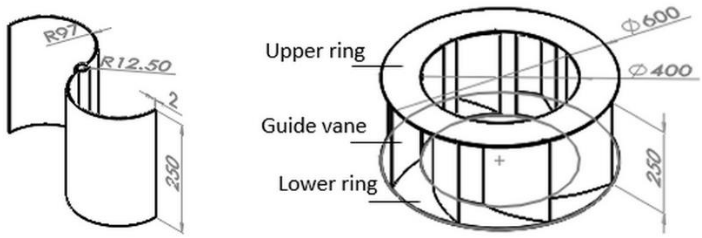

Fig. 2. VAWT and wind booster specification

2.2. CFD-based analysis

For CFD case studies, a Savonius-type VAWT and a preliminary design of wind booster [5] are investigated for genuine performances of mechanical behaviors. The material in modelling the VAWT is proposed to be a fiber plastic of 1000 kg/m^3. The dimensions of the VAWT and the wind booster are shown in Fig 2. The experiments are performed with CFD-based simulations by utilizing XFlow^{TM} CFD software [6]. To investigate how the wind booster has effect on the change of wind stream described by change in wind velocity and wind direction, the standalone wind booster is firstly tested under the wind stream of 3 m/s which represents the average low wind speed. Next, the stand-alone VAWT and the VAWT equipped with the wind booster are tested to investigate different performances on mechanical works. The simulations are divided into 2 cases: 1.) no loading condition and 2.) various loading conditions. In simulations, the wind speed is varied from 1 m/s to 8 m/s for low wind speed conditions. The VAWT is to turn in clockwise direction of the vertical axis under the frictionless rotation. For various loading conditions, external torques are applied to a shaft of the VAWT in counter clockwise direction.

The power output of the VAWT is generally determined as:

$$P_T = T\,\omega \tag{2}$$

where P_T is the power output of the VAWT (W), T is the torque of the VAWT (Nm) and ω is the angular speed of the VAWT shaft (rad/s).

3. Results and discussion

The main mechanism of a wind booster, as shown in Fig 3, can be separated into 2 functions. The former is “guiding”; the guide vanes direct wind to impact VAWT blades at effective angles. The latter is "throttling"; the passage between each guide vane is set up to throttle air flow to be accelerated before impacting VAWT blades. The simulated results in Fig 3 show that when the air at the region A flows along a positive X axis through the wind booster, the guide vanes lead the wind to the VAWT blades at the region B. The VAWT blades are effectively pushed by the wind in this region. Also, the guide vanes prevent the wind countering rotation of VAWT at the region C. The passage between two guide vanes is designed to throttle the wind to increase the wind speed. The wind speed at the region B is higher than the region A.

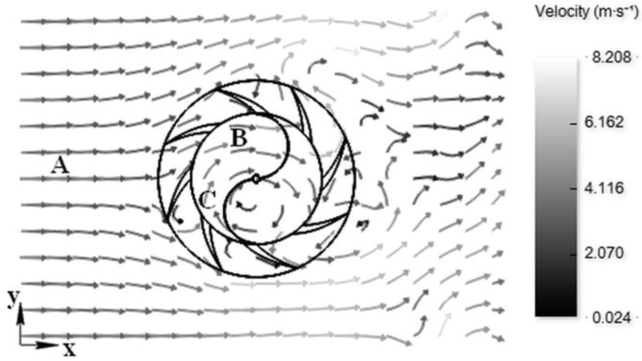

Fig. 3. CFD simulation of wind flow through the wind booster

3.1. No loading condition

Under a no loading condition, the simulated results on angular speed of the VAWT are reported in Fig 4. The curve of the VAWT speed in the case of the VAWT with the wind booster significantly shifts over the curve of the VAWT speed in the case of the VAWT without the wind booster. The wind booster is cable of increasing angular speeds of the VAWT by 50% of angular speeds of the VAWT without the wind booster at various wind speeds. This increment in speed of the VAWT results in great improvement of mechanical power generation.

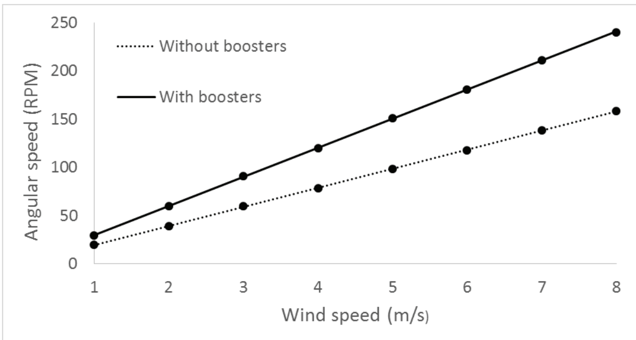

Fig. 4. Plots of VAWT angular speed against wind speed

3.2. Various loading condition

In Fig 5 and Fig 6, the VAWT is operated under load conditions. It can be observed that the higher the external torque is applied, the lower the angular speeds of the VAWT as usual. However, the torques of the VAWT with the wind booster in Fig 6 can be exerted at much higher comparatively. It can be interpreted that the VAWT with the wind booster is capable of generate higher mechanical powers as shown in Fig 7 and Fig 8. Obviously, the mechanical power of the VAWT with the wind booster is increased by the peak and it is expanded by the operating range of the angular speed of the VAWT significantly compared with the mechanical power generated by the VAWT without the wind booster.

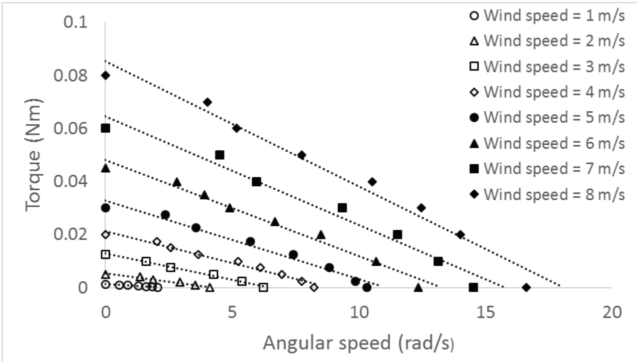

Fig. 5. Plots of torques against VAWT angular speeds without wind booster

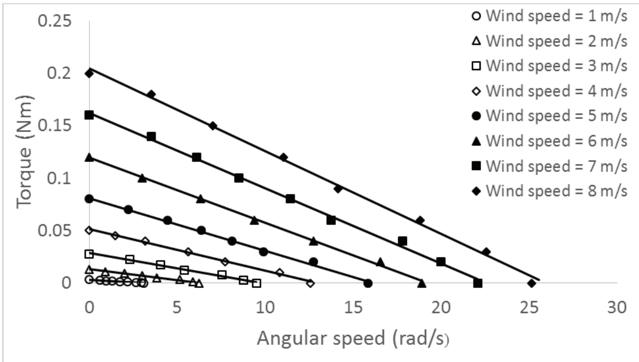

Fig. 6. Plots of torques against VAWT angular speeds with wind booster

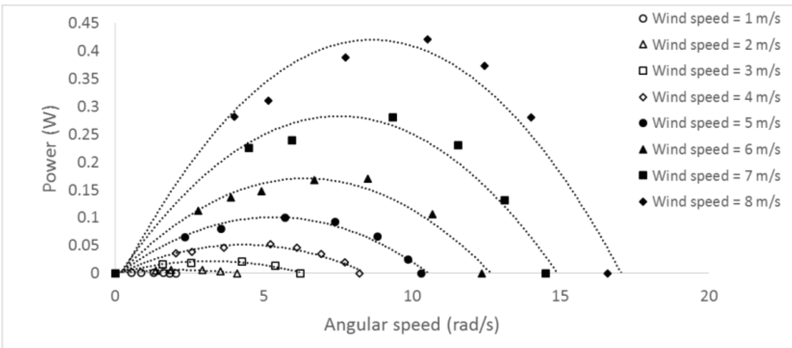

Fig. 7. Plots of mechanical powers against VAWT angular speeds without wind booster

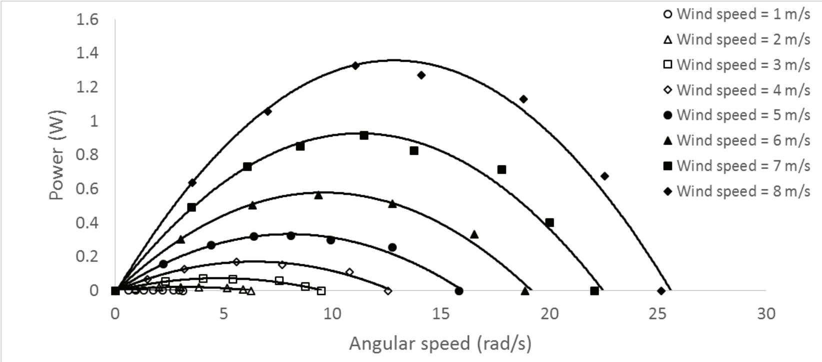

Fig. 8. Plots of mechanical powers against VAWT angular speeds with wind booster

4. Conclusion

The CFD experiments show that the specially-designed wind booster is able to improve performances of the VAWT at low speed wind conditions. It can be observed that from CFD case studies, guiding and throttling effects of the wind booster are able to increase angular speed of a VAWT which leads to increase in mechanical power generated from a VAWT.

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